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An Ideal Window Area concept for energy efficient integration of daylight and artificial light in buildings

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Abstract

There have been many developments in energy efficiency in buildings in the last few decades, but many new buildings are still not designed whereby daylight is efficiently integrated with the artificial lighting system. In cases where there is integration, the potential for energy savings to be made on lighting is not always assessed. This paper presents a methodology to predict the potential for energy savings on lighting using an Ideal Window Area concept when there is effective daylight integration with the artificial lighting system. The methodology was developed by using rooms of ten different dimensions and five different room ratios. The energy analysis work was performed using the VisualDOE programme for the climatic conditions of Leeds, in the UK, and Florianópolis, in Brazil. Following this, the potential for lighting energy savings was assessed for each room using a method based on Daylight Factors. It was observed that the potential for energy savings on lighting in Leeds ranged from 10.8% to 44.0% over all room sizes and room ratios for an external illuminance of 5000 lux; and in Florianópolis, the potential ranged between 20.6% and 86.2% for an external illuminance of 10000 lux. The methodology presented can be applied to any location around the world.

Keywords: Energy savings on lighting; Daylight; Daylight factors; Computer simulation

1. Introduction

Lighting systems are responsible for consuming large amounts of energy in buildings all around the world. Fortunately, advances have been made in lighting fitting design that have contributed to reduce this problem. It is reported that around 25% of the total electricity used in the commercial sector is consumed by lighting systems [1]. Consumption ranges greatly from country to country and is not only due to climatic and design conditions, but also to cultural habits. In China, the lighting end-use in commercial buildings is 15% [2]; in the USA, 39% [3]; in the Netherlands, 55% [4]; and in the UK it ranges from 30% to 60% [5]. In Brazil, the lighting end-use in commercial buildings with air-conditioning is about 24%; but in commercial buildings without air-conditioning, the lighting end-use can reach 70% of the energy consumption of the whole building [6].

Energy efficiency in a lighting system can be achieved mainly through the minimisation of two variables: the lighting power density and the lighting system use. A reduction of the lighting power density, which is the ratio of total lamp wattage in a room to its floor area, can be obtained through the use of energy efficient lamps, luminaires and associated equipment. However, it must also be noted that energy efficient equipment—widely available in the market—does not provide for energy savings by itself. A lighting design needs to be carried out following all the steps required by this kind of design and the user requirements must be considered. In brief, one needs not only to use energy-efficient equipment, but also an energy-efficient lighting design [7]. The second variable—the lighting system use—could be optimised through the use of control systems and also through the effective integration of daylight. Such an approach could reduce energy consumption and promote energy efficiency in the building.

The effective integration of the artificial lighting system and daylight occurs only when the artificial lighting system can be switched on or off as a function of daylighting levels reaching the working surface. Large window areas allow more daylight into a space, but they may also allow excessive heat gains or losses which increases the air-conditioning cooling or heating load and consequently the energy

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consumption. Specifying an Ideal Window Area for a space in which there is a balance between daylight provision and solar thermal load would lead to a scenario whereby the energy consumption of the space is optimised. This method is therefore being proposed as a strategy to improve the energy efficiency in buildings.

2. Objectives

The main objective of this paper is to present a methodology to predict the Ideal Window Area of spaces and to assess the potential for lighting energy savings due to the integration of daylight. The methodology is then applied to two case studies to determine the Ideal Window Area and the potential for lighting energy savings for one city in the UK and one in Brazil.

3. Methodology

To accomplish the objective above specified, it was initially necessary to select and use a Dynamic Thermal Modelling (DTM) code to identify the window area of rooms of different sizes and different room ratios in which there is a balance between solar thermal load and daylight supply. Such a window area is referred to as the Ideal Window Area and is the one in which the energy consumption for the room is the lowest. The DTM code selected was VisualDOE [8] because it offered the capability of simulating a wide range of design features and energy conservation measures including the integration of daylight with artificial light. It has also been widely validated for accuracy and consistency [9–12]. The programme utilises the DOE-2 calculating engine, which performs building energy analyses given a description of the climate, architecture and thermo-physical properties of the building components, operating schedules and HVAC equipment [13].

Though validations on DOE have been widely reported, prior to using VisualDOE, it was validated using parameters specific to this work. Once validation had been completed, rooms of different sizes, different window areas, and different room ratios were then simulated in order to identify their Ideal Window Area. To assess the potential for energy savings on the artificial lighting system that can be obtained by effective integration of daylight reaching the working surface via the Ideal Window Area, Daylight Factors were calculated for each room. The following sub-sections describe the methodology used and Section 4 presents the validation of the VisualDOE programme and also the validation of the sky component, which is a component of the Daylight Factor.

3.1. The Ideal Window Area

The Ideal Window Areas of the various room ratios used were determined using a model building 10 storeys high. The model comprises rooms whose ratio of width to depth were 2:1, 1.5:1, 1:1, 1:1.5, and 1:2, respectively, as shown in Fig. 1. These five room ratios were chosen in order to compare the amount of daylight reaching the working surface in wide-shallow rooms with the amount of daylight reaching the working surface in narrow-deep rooms.

In order to evaluate the influence of the size of the room on the supply of daylight, each room ratio was assessed over ten different room sizes. So as not to use random room sizes, the dimensions of each room were calculated as a function of the Room Index (K), as used in artificial lighting design. Eq. (1) presents the room index formula [14].

$$K = \frac{WD}{(W + D)h}, \tag{1}$$

where K is the room index (non-dimensional), W is the overall width of the room (m), D is the overall depth of the room (m) and h is the mounting height between the working surface and the ceiling (m).

Such an index represents the relationship between area, perimeter and mounting height between the working surface and the ceiling. Generally in literature, ten room indices varying from 0.60 (small rooms) to 5.00 (large rooms) are used.

Having defined the five room ratios, the width of the room can be expressed as a function of the depth, or vice versa, and Eq. (1) can be rewritten as follows:

$$\text{When the room ratio is 1:1, } D = W, \text{ then } W = 2Kh, \tag{2}$$

When the room ratio is 1:1.5, $D = 1.5W$,

$$\text{then } W = \frac{2.5}{1.5} Kh, \tag{3}$$

When the room ratio is 1.5:1, $W = 1.5D$,

$$\text{then } D = \frac{2.5}{1.5} Kh, \tag{4}$$

When the room ratio is 1:2, $D = 2.0W$,

$$\text{then } W = \frac{3.0}{2.0} Kh, \tag{5}$$

When the room ratio is 2:1, $W = 2.0D$,

$$\text{then } D = \frac{3.0}{2.0} Kh. \tag{6}$$

Table 1 presents the room dimensions for each of the ten room indices and five room ratios calculated using Eqs. (2)–(6). The overall height of the rooms was taken to be 2.80 m and the working surface to be 0.75 m above floor level, so that $h = 2.05$ m.

In order to determine the Ideal Window Area of each room, simulations using VisualDOE were performed considering incremental glazed façade areas ranging from 0% to 100% at increments of 10% (Fig. 2).

The energy consumption of a building depends, amongst other factors, on climatic conditions and on the availability

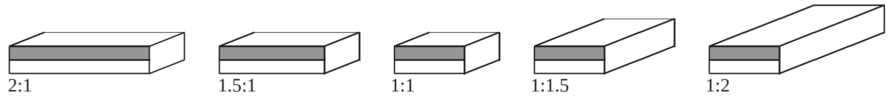

Fig. 1. Isometric view showing the five room ratios.

Table 1
Room dimensions for each room index (K) and room ratio

K	Room ratio									
	2:1		1.5:1		1:1		1:1.5		1:2	
	W (m)	D (m)	W (m)	D (m)	W (m)	D (m)	W (m)	D (m)	W (m)	D (m)
0.60	3.69	1.85	3.08	2.05	2.46	2.46	2.05	3.08	1.85	3.69
0.80	4.92	2.46	4.10	2.73	3.28	3.28	2.73	4.10	2.46	4.92
1.00	6.15	3.08	5.13	3.42	4.10	4.10	3.42	5.13	3.08	6.15
1.25	7.69	3.84	6.41	4.27	5.13	5.13	4.27	6.41	3.84	7.69
1.50	9.23	4.61	7.69	5.13	6.15	6.15	5.13	7.69	4.61	9.23
2.00	12.30	6.15	10.25	6.83	8.20	8.20	6.83	10.25	6.15	12.30
2.50	15.38	7.69	12.81	8.54	10.25	10.25	8.54	12.81	7.69	15.38
3.00	18.45	9.23	15.38	10.25	12.30	12.30	10.25	15.38	9.23	18.45
4.00	24.60	12.30	20.50	13.67	16.40	16.40	13.67	20.50	12.30	24.60
5.00	30.75	15.38	25.63	17.08	20.50	20.50	17.08	25.63	15.38	30.75

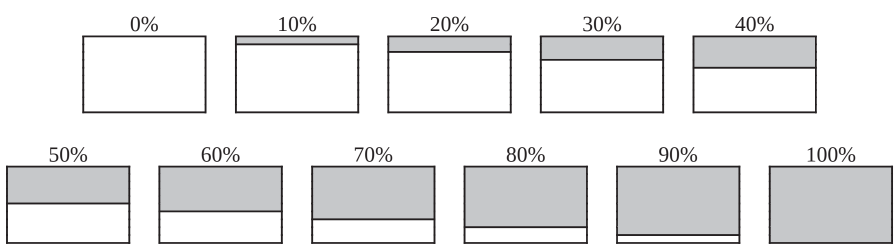

Fig. 2. Glazed areas of the room façades simulated.

of daylight if there is to be integration with the artificial lighting system. Because of the former dependency, the energy consumption of the model building was simulated under different climatic conditions. The research was undertaken in the UK, therefore a UK city was deemed appropriate. Access to climatic data for cities in Brazil was available over a range of climates, therefore a Brazilian city was selected to complement the climatic difference required [15].

In the UK, the city of Leeds was selected and relevant climatic data was obtained from the British Atmospheric Data Centre covering the period April 1999–March 2000. This was then converted to a format recognisable by the VisualDOE programme. In Brazil, the city of Florianópolis was selected. The climatic data was once again converted to a form recognisable by the VisualDOE programme, this being in the form of a Test Reference Year [16].

As mentioned previously, geographical location is a factor that affects daylight availability, therefore the latitude and longitude of the two cities selected are shown in Table 2.

Table 2
Latitude and longitude of the two cities

City	Latitude	Longitude
Leeds (UK)	53°48′	−1°34′
Florianópolis (Brazil)	−27°36′	−48°33′

All the VisualDOE simulations took account of the differences in building use between England and Brazil, such as occupancy schedules, building components, climate etc. For example, for the simulation using the model building in Leeds, a set-point temperature of 23°C was assumed for summer cooling and 20°C for winter heating. The occupancy schedule was assumed to be 100% between 9a.m. and 5p.m., Monday to Friday, with artificial lighting and equipment operating over the same period. For the simulations using the model building in Florianópolis, the set-point temperature for summer cooling was assumed to be 24°C, with no heating over the winter period as this is common practice in Brazil. The occupancy schedule considered an occupation of 100% between 8a.m.–12noon and 2p.m.–6p.m., Monday

Table 3
Thermal properties of walls and roof used in the simulations

Component	Leeds (UK)			
	U (W/m^2 K)	HC (kJ/m^2 K)	Solar absorption (%)	Light transmission (%)
Walls	0.45	324	50	
Roof	0.25	228	70	
Window	5.7	—	—	88
	Florianópolis (Brazil)			
Walls	1.92	202	70	
Roof	2.22	77	70	
Window	5.7	—	—	88

to Friday, with artificial lighting and equipment operating over the same period.

The thermal properties of the walls and roof were considered differently for each country as shown in Table 3. This is due to the fact that the adopted values attempt to represent common practice in both countries. U stands for U-value and HC for heat capacity.

Simulating the building in VisualDOE using all the above values enabled the energy consumption to be obtained at each 10% increment of window area for each room. The Ideal Window Area was then determined as being the one in which the energy consumption of the room was the lowest.

3.2. The potential for energy savings

Having determined the Ideal Window Areas for all the rooms, the potential for energy savings to be made on the artificial lighting was then calculated based on Daylight Factors. The procedure used to calculate the Daylight Factors is the same as presented in [17–19].

Daylight Factors represent the ratio of indoor to outdoor daylight illuminance under a standard overcast sky condition. The Daylight Factor represents the total daylight reaching a reference point in the interior of a room and comprises three components:

(a) The sky component—daylight on the reference point in the room received directly from the sky.

(b) The external reflected component—daylight on the reference point reflected into the room by any external surfaces.

(c) The internal reflected component—daylight on the reference point reflected and inter-reflected at the surfaces inside the room.

These three components are calculated separately and the Daylight Factor is the summation of the three values.

3.2.1. The sky component

There are different methods of calculating the sky component. It can be based on tables, protractors, diagrams, or graphical methods. Due to the large number of Daylight Factor calculations needed in this work, it was decided to use the BRS Simplified Daylight Tables [17,18]. The sky component is determined by a geometrical procedure and the BRS Simplified Daylight Tables are designed to provide the sky component as a function of the geometry of the window taken at each reference point.

Although the Commission Internationale de L'Éclairage (CIE) overcast sky has been acknowledged to underestimate illuminance levels in side-lit rooms [20,21], this was the sky luminance condition chosen. This sky is the one whose horizon is darker than the zenith and its luminance does not vary with azimuth.

3.2.2. The externally reflected component

The externally reflected component can be calculated by considering the external obstructions visible from the reference point as a patch of sky whose luminance is some fraction of that of the sky obscured [18]. This component is usually calculated as a fraction of the sky component as the luminance of the obstructing surfaces is assumed to be uniform and one-tenth of the average luminance of the sky. As the luminance of an overcast sky near the horizon is approximately half the average luminance—and this correction has already been considered in the BRS Simplified Daylight Table—the externally reflected component is then obtained dividing the sky component by 5 [18].

3.2.3. The internally reflected component

The internally reflected component depends upon the reflectances of the walls, ceiling and floor of the room, and upon the amount of daylight that reaches them from the sky and the obstructions and ground outside. The process of reflection and inter-reflection is complex and the amount of inter-reflected daylight varies according to the distance of the reference point from the window. However, as stated in [19], for most purposes it is sufficient to assume an average internally reflected component. Eq. (7) presents the formula to calculate the average internally reflected component

Table 4
Number and dimensions of squares for each room index and room ratio

K	Room ratio					
	1:1		1.5:1 & 1:1.5		2:1 & 1:2	
	Number of squares	Dimension (cm)	Number of squares	Dimension (cm)	Number of squares	Dimension (cm)
0.60	25 (5 × 5)	49 × 49	24 (4 × 6)	51 × 51	28 (4 × 7)	46 × 53
0.80	49 (7 × 7)	47 × 47	40 (5 × 8)	55 × 51	50 (5 × 10)	49 × 49
1.00	64 (8 × 8)	51 × 51	70 (7 × 10)	49 × 51	72 (6 × 12)	51 × 51
1.25	100 (10 × 10)	51 × 51	117 (9 × 13)	47 × 49	120 (8 × 15)	48 × 51
1.50	144 (12 × 12)	51 × 51	150 (10 × 15)	51 × 51	162 (9 × 18)	51 × 51
2.00	256 (16 × 16)	51 × 51	294 (14 × 21)	49 × 49	300 (12 × 25)	51 × 49
2.50	441 (21 × 21)	49 × 49	442 (17 × 26)	50 × 49	465 (15 × 31)	51 × 50
3.00	625 (25 × 25)	49 × 49	651 (21 × 31)	49 × 50	666 (18 × 37)	51 × 50
4.00	1089 (33 × 33)	50 × 50	1107 (27 × 41)	51 × 50	1225 (25 × 49)	49 × 50
5.00	1681 (41 × 41)	50 × 50	1734 (34 × 51)	50 × 50	1922 (31 × 62)	50 × 50

(IRC) for side-lit rooms.

$$\text{Average IRC} = \frac{0.85W}{A(1-R)}\,(CR_{\text{fw}} + 5R_{\text{cw}}), \tag{7}$$

where W is the area of window (m^2), A is the total area of ceiling, floor and walls including the area of the window (m^2), R is the average reflectance of ceiling, floor and all walls, including window, expressed as a fraction, R_{fw} is the average reflectance of the floor and those parts of the walls below the plane of the mid-height of the window, excluding the window wall, R_{cw} is the average reflectance of the ceiling and those parts of the walls above the plane of the mid-height of the window, excluding the window wall and C is a coefficient having values dependent on the angle of obstruction outside the window. As obstructions were not considered, the C coefficient is to be 39 [19].

Having determined the three components, the Daylight Factors were then calculated on the working surface of each room in order to obtain the potential for energy savings on the artificial lighting when there is integration with daylight. To accurately evaluate the distribution of daylight in the rooms, the working surface of each room was divided into a number of hypothetical squares of approximately 50×50 cm each. The Daylight Factor was then calculated at the centre of each square. Table 4 presents the number of squares (and their dimensions) calculated for each room index and room ratio.

As noted previously, the determination of the internally reflected component depends on the reflectances of the internal surfaces of the space. British Standard 8206-1 [22] states that such surfaces should be light in colour to improve the efficiency of the lighting system. As furnishings in the space tend to reduce such reflectances, the internal surface reflectances assumed in the calculation of the Daylight Factors are presented in Table 5.

3.2.4. Procedure for estimating energy savings on artificial lighting

Having calculated the Daylight Factors as previously described and the Ideal Window Area for each room size, the procedure used to estimate the energy savings that could be made on the artificial lighting system could then be completed.

Table 5
Reflectance of the internal surfaces

Surface	Reflectance (%)
Wall	50
Ceiling	70
Floor	30
Window	10

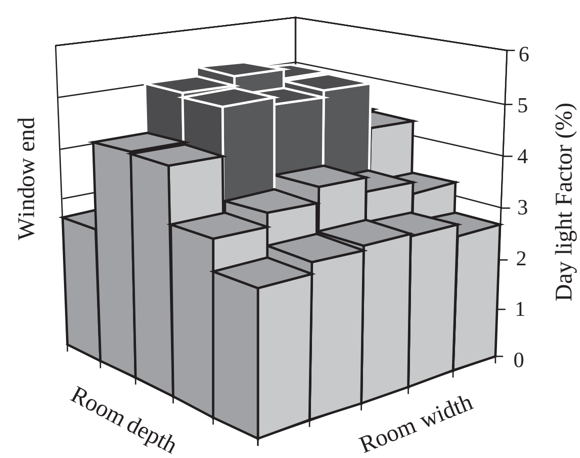

Fig. 3. Daylight Factors for a room of room ratio 1:1, room index 0.60 and Ideal Window Area 21%.

As an example of the method, Fig. 3 shows the Daylight Factors calculated in the centre of each of the 25 squares of a room whose room ratio is 1:1, room index 0.60, and Ideal Window Area 21% (Florianópolis, south orientation). An estimation of the energy savings that could be made on the artificial lighting was based on the following assumptions:

(a) If the lowest calculated Daylight Factor in the room were equal to or higher than the design Daylight Factor, the daylight reaching the working surface in the room would be sufficient to supply the lighting requirement over all the working surface and there would be no need for artificial lighting.

(b) If the highest calculated Daylight Factor were lower than the design Daylight Factor, the daylight levels on the working surface would be lower than the requirements, but should not be overlooked as they could contribute to energy savings if they were integrated with the artificial lighting.

Therefore, two assessments were performed in order to estimate the energy savings likely to be achieved on the artificial lighting system. First, the percentage of floor area near the window, in which the Daylight Factors are higher than the design Daylight Factor, was calculated. Then, for the rest of the room, where the Daylight Factors are lower than the design Daylight Factor, the percentage contribution of each Daylight Factor compared to the design Daylight Factor was also calculated. The percentages mentioned above can be easily calculated because each Daylight Factor represents the same fractional area of the room (the squares have the same dimensions). As an example, in Fig. 3, when the design Daylight Factor is for instance 5%, there are 6 squares whose Daylight Factor is equal to or higher than 5%—these are shown in black. Therefore, the percentage of the room area in which the artificial lighting system could be switched off is 24.0%, as obtained from Eq. (8).

$$S_{\text{front}} = 100 \times \frac{6}{25} = 24.0\%, \tag{8}$$

where S_{front} is the percentage floor area at the front of the room, 6 is the number of locations in which the Daylight Factors are higher than 5% and 25 is the total number of locations.

The Daylight Factors lower than 5% are shown in grey. It is suggested that the artificial lighting system at the rear of the room be considered only to supplement the lighting requirements as the Daylight Factors in this area, though lower than the design Daylight Factor of 5%, can still contribute to energy savings. This can be evaluated by calculating the percentage contribution of each Daylight Factor lower than the 5% value. For this example, the daylight at the rear of the room, represented by Daylight Factors in grey, supplies 66.6% of the lighting requirement as shown by Eq. (9).

$$S_{\text{rear}} = 100\,\frac{\sum_1^{19} \frac{DF}{5}}{19} = 100\,\frac{\frac{2.63}{5} + \frac{4.34}{5} + \cdots + \frac{3.26}{5} + \frac{2.67}{5}}{19}$$
$$= 66.6\%, \tag{9}$$

where S_{rear} is the supply of daylight away from the window to the sides and to the rear of the room, DF are the individual values of Daylight Factors that are lower than 5% (19 in total).

Taking into account that the artificial lighting system is usually evenly distributed over the ceiling area, the savings calculated through these models can be assumed to represent savings on the artificial lighting system.

For the example being used, where 24.0% of the floor area has Daylight Factors higher than the design Daylight Factor, it can be stated that 100% of the lighting power density (W/m^2) can be assumed to be turned off over 24.0% of the room area. For the rest of the room (76.0% of the floor area), 66.6% of the lighting power density could be dimmed off (Eq. (9)). Therefore, the total energy savings that could be made on the artificial lighting system would be 75.0% (see Eq. (10)) when the design Daylight Factor is 5% and if the room were equipped with a dimmer system.

$$S_{\text{total}} = 100\,(S_{\text{front}} + (1 - S_{\text{front}})S_{\text{rear}})$$
$$= 100\,(0.240 + (1 - 0.240)0.666) = 75.0\%, \tag{10}$$

where S_{total} is the total percentage energy savings that could be made on the artificial lighting system.

4. Validation

This section presents the validation of the VisualDOE programme and also of the method to determine the sky component.

4.1. The VisualDOE programme

Validations of the DOE programme have been widely reported and these confirm that the software can simulate reliable data when the input data is correctly modelled. To confirm previous reports, the programme was validated using specific parameters related to this work.

For the validation, results of monthly energy consumptions measured over a year in a building located on the campus of Leeds University, UK, were compared to results simulated by the programme. A building was chosen due to the nature of the office activities taking place in it and because of the interest of the Energy Manager in evaluating the potential for making energy savings. The building is three storeys high, measuring 8 m × 20 m on plan. Each floor comprises offices of different dimensions [15].

Table 6 presents the measured and simulated energy consumption for the building between the period April 1999 and March 2000 as simulated by the VisualDOE programme. The right-hand column shows the percentage difference between the two values. The highest difference between the measured and simulated energy consumption occurred in May 1999 with a discrepancy of 20.6%. Though high, the difference lies within the error range considered acceptable by ASHRAE [23] and Zmeureanu et al. [24].

4.2. The sky component

Of the three components that compose the Daylight Factor, the sky component is the most important as it depends on assumptions related to sky conditions. Therefore, to confirm that the Daylight Factors calculated in this work would provide reliable data, a model was built and daylight levels were measured in order to validate the sky component.

Table 6
Measured versus simulated energy consumption

Month/year	Energy consumption (kWh)		Difference (%)
	Measured	Simulated	
April/99	11890	11883	−0.1
May/99	9901	11941	20.6
June/99	9772	11377	16.4
July/99	10429	11381	9.1
August/99	12033	12039	0.0
September/99	11638	11144	−4.2
October/99	14782	13385	−9.4
November/99	15295	15536	1.6
December/99	16388	16983	3.6
January/00	17350	17914	3.3
February/00	16668	15064	−9.6
March/00	18591	15513	−16.6
Total	164737	164160	−0.4

The model comprised a square box of dimensions $41.0 \times 41.0 \times 11.2$ cm high, which represents an actual room of $10.25 \times 10.25 \times 2.80$ m reduced to a scale of 1:25. The room index of both the model and the actual room was $K = 2.50$. As the objective of this experiment was to validate the sky component, models of any dimensions could have been used provided that the sky components were calculated for a model of same dimensions and conditions.

The internal surfaces of the scale model were painted matt black to reduce reflections as the intention was to determine the sky component only. Daylight levels were measured at a point outside the model and at three reference points inside the model which are shown in Fig. 4(a). The window of the model occupied 73.2% of the façade area. It was not glazed and its height and geometry are shown in Fig. 4(b). The window sill height coincided with the level of the working surface at 3.00 cm.

Daylight measurements were performed daily between 22 and 25 February 2000 on the roof of the Civil Engineering Building, University of Leeds. Two calibrated (to ISO 9001) portable luxmeters were used for the measurements.

As the sky component comprised a single value at each reference point, it was decided to perform repeated sets of measurements in order to obtain an average sky component at each point and to compare the average with the calculated value. Ten sets of measurements were taken at each reference point on each of four days over an interval of about 5 min. Each internal measurement was immediately followed by an external one, so that the sky component could be calculated. An average sky component value was then calculated for each point.

Fig. 5 shows the measured sky components over the four days and also the calculated values at the same points. The comparison of measured and calculated sky components agreed closely, therefore the sky components used in the calculations of Daylight Factors were assumed to provide reliable data.

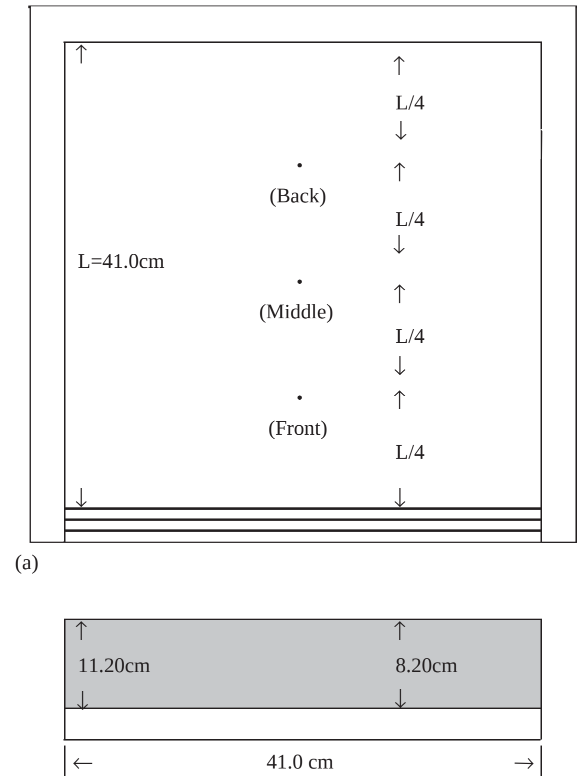

Fig. 4. (a) Plan view and (b) façade of the model.

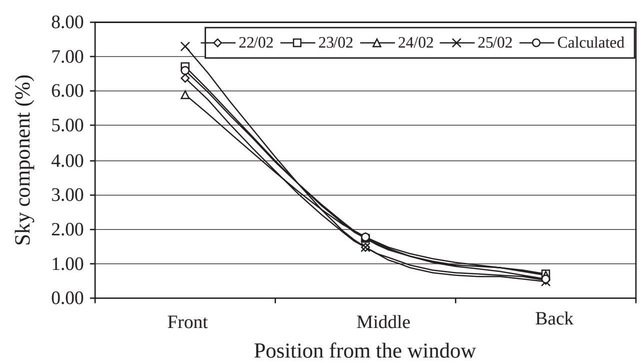

Fig. 5. Measured versus calculated sky components.

5. Results

5.1. The Ideal Window Area

From the results of the energy consumption of a building as a function of window area obtained from the simulations using the VisualDOE programme, the Ideal Window Area was obtained for each of the ten room sizes (room indices), five room ratios, and on four orientations for Leeds and

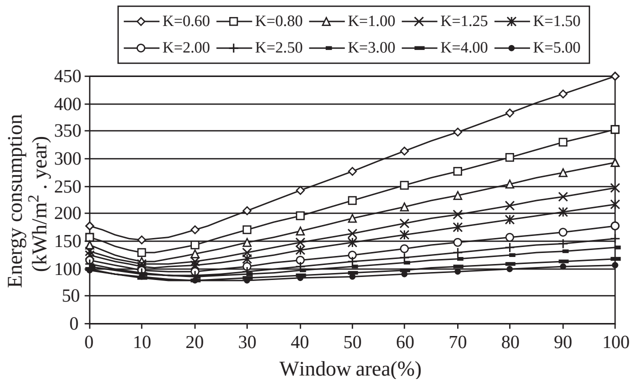

Fig. 6. Energy consumption for Florianópolis, room ratio of 2:1, North orientation.

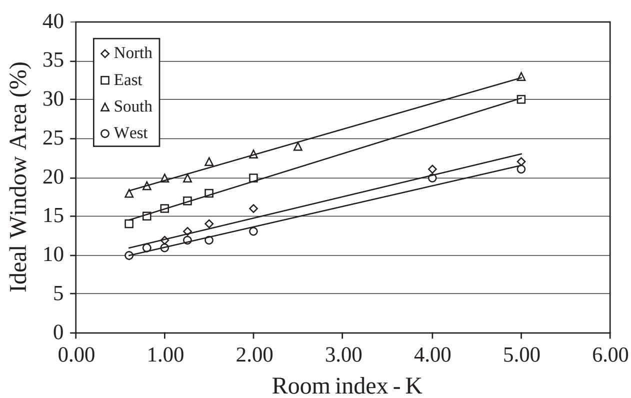

Fig. 7. Ideal Window Area versus room indices for Florianópolis, room ratio 2:1.

Florianópolis. As an example, Fig. 6 presents the results of the energy consumption of the model building when located in Florianópolis, room ratio of 2:1, North orientation. The first observation that can be made from the figure is that the energy consumption per floor area decreases as the room indices increase. In terms of window area, it can be observed that the Ideal Window Area is larger for larger rooms (larger room index). The Ideal Window Areas were obtained using a best-fit polynomial line for each case. From Fig. 6 it can be observed that the Ideal Window Areas range from 10% ($R^2 = 0.9999$) for $K = 0.60$ to 22% ($R^2 = 0.9979$) for $K = 5.00$.

The Ideal Window Areas obtained from Fig. 6 were then plotted as a function of the room indices as shown in Fig. 7, where the Ideal Window Areas for the other three orientations are also shown. It was noted that there is a linear increase of the Ideal Window Area as the room index increases. Therefore, a best-fit straight line and the equivalent equation were determined to express the Ideal Window Area as a function of the room index for each orientation. This procedure was then adopted to determine the Ideal Window Area over the different room sizes, room ratios, and different orientations for the two cities.

Tables 7 and 8 show the Ideal Window Areas for each room index, room ratio, and orientation for buildings in the cities of Leeds and Florianópolis, respectively. In these tables, N stands for North, E for East, S for South, and W for West. It can be observed that the Ideal Window Area increases in larger rooms (those with a larger room index —K) and also in rooms with a narrower width (from room ratio 2:1 towards 1:2) for both cities. It can also be noted that for buildings in Leeds, the Ideal Window Area tends to be larger on the North orientation, as the city is located in the northern hemisphere and the solar thermal load on this orientation is negligible.

For Florianópolis, the Ideal Window Area tends to be larger on the East and South orientations as the solar thermal load is lower on these. The Ideal Window Area also has a tendency to be smaller on the West orientation as this is the orientation under the most severe solar condition.

The walls that contain the windows present different sizes for the different room ratios, therefore the real window sizes are also different for the same room index. For example, taking a room index of 0.60 and room ratios of 2:1 and 1:1, respectively (from Table 7), both rooms have an IWA of 16% on the North orientation. This represents a window area of 1.65 m^2 when the room ratio is 2:1 and 1.10 m^2 when the room ratio is 1:1. As expected, the two rooms would show a different potential for energy savings as shown (Table 9).

5.2. The potential for energy savings

Results showing the potential for energy savings on the artificial lighting due to daylight entering the room through the Ideal Window Area are shown in Tables 9 and 10 for Leeds and Florianópolis, respectively. The data shown in these tables are based on an illuminance level on the working surface of 500 lux for both cities. An average outdoor illuminance of 5000 lux was assumed for Leeds, which is approximately the figure used in daylight design in the UK. For Florianópolis, an outdoor illuminance of 10000 lux was assumed as this is a typical value from an overcast sky [25]. These relatively low illuminance levels ensure that the energy savings presented in the tables are the minimum that can be expected to be made on the artificial lighting.

The data shown in the tables indicate that there is a tendency for energy savings on lighting to be greater for smaller room indices (K) and for room ratios whose room width is larger. Table 9 shows the results of energy savings on lighting likely to occur in Leeds when there is integration of daylight coming into the rooms from the Ideal Window Area with the artificial lighting system. The energy savings likely to be achieved range from 10.8% to 44.0%. Results obtained for Florianópolis are presented in Table 10 and it can be observed that energy savings on lighting range from 20.6% to 86.2%.

Table 7
Ideal Window Areas for Leeds, England (% of the room façade area)

K	2:1				1.5:1				1:1				1:1.5				1:2			
	N	E	S	W	N	E	S	W	N	E	S	W	N	E	S	W	N	E	S	W
0.60	16	11	10	7	19	12	11	7	16	16	11	7	18	20	11	8	23	20	14	9
0.80	18	12	11	7	20	13	11	7	18	17	12	7	21	21	12	9	26	21	14	10
1.00	19	13	11	8	21	14	12	8	20	17	12	8	24	22	13	10	29	23	15	11
1.25	21	13	11	8	23	15	12	8	23	18	13	9	27	24	14	11	32	25	17	12
1.50	23	14	12	9	25	16	12	9	26	20	14	10	31	25	16	12	36	27	18	13
2.00	27	16	13	10	28	19	13	10	31	22	15	11	37	28	18	14	43	31	20	15
2.50	30	17	14	11	31	21	14	11	37	24	17	13	44	31	20	15	50	35	22	18
3.00	34	19	14	12	34	23	14	12	42	26	18	14	51	34	22	17	58	39	25	20
4.00	41	22	16	14	40	28	16	14	53	31	21	18	65	40	27	21	72	47	29	24
5.00	49	25	18	16	47	32	17	17	64	35	24	21	79	46	32	25	87	55	34	29

Table 8
Ideal Window Areas for Florianópolis, Brazil (% of the room façade area)

K	2:1				1.5:1				1:1				1:1.5				1:2			
	N	E	S	W	N	E	S	W	N	E	S	W	N	E	S	W	N	E	S	W
0.60	11	15	18	10	11	15	20	10	16	19	21	12	20	25	25	15	25	26	31	19
0.80	11	15	19	11	12	16	21	11	17	19	22	12	21	26	26	16	27	27	33	19
1.00	12	16	20	11	13	17	22	11	18	20	24	13	22	27	28	17	28	29	36	20
1.25	13	17	20	12	14	18	23	12	19	21	25	14	24	28	30	17	29	31	38	21
1.50	13	18	21	12	15	19	24	13	20	22	27	15	25	29	32	18	31	32	41	21
2.00	15	20	23	14	17	20	26	15	21	24	30	16	27	31	36	20	34	36	47	23
2.50	16	21	25	15	19	22	28	16	23	26	33	18	30	34	40	22	37	40	53	25
3.00	18	23	26	16	22	24	30	18	25	28	36	19	32	36	44	23	40	43	58	26
4.00	21	27	30	19	26	28	35	21	29	32	43	22	37	41	52	27	45	50	69	29
5.00	24	30	33	22	30	31	39	24	33	36	49	25	42	46	59	30	51	58	81	33

Table 9
Potential for energy savings (%) on artificial lighting when using the Ideal Window Area concept in Leeds with an outdoor illuminance of 5000 lux

K	2:1				1.5:1				1:1				1:1.5				1:2			
	N	E	S	W	N	E	S	W	N	E	S	W	N	E	S	W	N	E	S	W
0.60	41.0	25.8	22.4	17.2	41.0	24.2	23.5	12.5	27.1	27.1	17.9	11.9	26.9	29.4	16.0	10.9	28.3	24.5	17.3	10.8
0.80	43.3	27.7	23.3	15.6	44.0	29.8	22.4	16.5	30.5	29.3	21.2	10.7	29.6	29.6	16.0	11.3	30.7	23.9	16.0	10.9
1.00	41.6	28.2	25.1	16.8	42.7	29.2	23.3	15.9	33.3	28.9	19.3	11.9	31.6	28.9	16.3	12.9	32.2	24.8	15.0	12.0
1.25	43.7	25.1	22.0	15.3	42.4	29.2	21.6	14.0	35.3	27.8	19.2	13.5	33.2	28.5	16.6	12.5	33.0	25.0	16.7	11.2
1.50	43.9	25.1	22.1	16.1	43.5	26.6	19.7	14.1	37.1	27.7	18.4	13.9	35.3	28.0	17.1	12.6	33.0	24.3	16.1	11.1
2.00	43.2	25.0	20.0	16.1	41.4	28.3	19.1	14.8	37.0	25.4	26.5	13.3	33.6	26.2	16.8	13.2	30.9	23.5	15.0	10.9
2.50	40.9	23.6	18.2	15.7	38.0	26.1	17.0	13.8	36.1	24.1	16.7	13.3	32.3	24.7	15.6	11.4	28.0	22.3	14.1	11.5
3.00	39.0	22.3	15.9	14.1	35.4	24.7	15.4	12.6	34.1	22.5	15.7	12.2	29.5	22.8	15.1	7.8	26.3	21.4	14.0	11.0
4.00	35.6	20.7	14.2	13.2	31.9	23.5	13.6	11.4	29.9	21.4	14.1	12.6	26.0	20.9	15.1	11.8	22.5	19.2	13.3	10.9
5.00	31.8	19.1	13.9	11.9	28.6	22.3	12.2	12.2	26.8	19.7	13.7	12.4	24.0	18.7	14.5	11.5	20.5	16.8	12.4	10.8

6. Conclusions

The following are the major findings from the analysis of using the Ideal Window Area concept in conjunction with daylight integration to evaluate the potential for energy savings on artificial lighting:

(1) The methodology presented can be applied to determine the Ideal Window Area for any space and the potential for energy savings on artificial lighting in any city worldwide.

(2) In terms of room sizes, it was shown that smaller rooms and rooms with a greater width, have a greater potential for energy savings on lighting due to daylight reaching the working surface through windows. This occurs because smaller rooms present a larger window-to-floor ratio. In terms of room ratio, rooms of greater width tend to

Table 10
Potential for energy savings (%) on artificial lighting when using the Ideal Window Area concept in Florianópolis with an outdoor illuminance of 10000 lux

K	2:1				1.5:1				1:1				1:1.5				1:2			
	N	E	S	W	N	E	S	W	N	E	S	W	N	E	S	W	N	E	S	W
0.60	51.6	69.2	82.2	44.8	47.0	60.6	86.2	42.2	54.1	61.6	75.0	42.4	58.8	74.3	74.3	45.2	64.4	66.7	74.8	48.9
0.80	46.6	69.1	84.7	46.6	56.0	70.4	85.8	44.8	58.6	67.6	76.6	42.5	61.1	71.6	71.6	44.0	62.3	62.3	69.7	44.4
1.00	51.4	70.6	83.2	50.2	52.5	67.5	84.1	42.4	60.6	66.2	74.8	42.0	56.1	64.6	66.1	45.0	58.1	58.2	65.7	43.4
1.25	50.2	65.3	76.9	45.0	52.3	63.9	75.0	43.2	55.7	62.1	69.7	40.2	53.5	60.2	62.3	40.7	50.5	54.1	59.1	40.8
1.50	47.8	66.2	72.8	44.2	51.0	60.1	71.0	42.6	53.8	56.9	65.0	39.0	50.7	54.7	58.5	38.9	48.8	49.2	54.7	37.1
2.00	44.8	59.4	64.4	42.4	47.7	55.3	64.6	43.2	46.8	50.7	58.4	37.2	44.6	47.8	51.4	36.0	41.7	43.2	48.1	32.8
2.50	42.7	53.0	59.5	38.7	44.6	49.3	57.0	37.7	43.2	46.3	53.1	35.6	39.9	42.9	46.5	33.3	37.0	38.6	43.6	28.9
3.00	41.5	48.6	53.1	37.5	44.4	45.8	52.5	37.7	38.5	42.1	47.8	32.5	36.2	38.1	42.1	28.8	33.9	35.1	40.1	26.7
4.00	36.6	43.8	46.3	34.8	38.9	40.5	45.6	34.1	35.1	36.2	41.7	28.4	31.4	32.8	36.8	26.3	28.9	30.2	34.6	22.7
5.00	32.4	38.0	40.4	31.4	35.0	36.0	40.1	30.0	30.8	32.1	37.2	25.7	27.8	29.0	32.4	23.3	25.3	26.9	30.6	20.6

provide more energy savings on lighting due to the integration of daylight and artificial light.

(3) The Ideal Window Area tends to be larger on the orientations whose energy consumption is lower due to the smaller solar thermal loads reaching the façade. This in turn increases the potential for energy savings due to daylighting contributions.

(4) The larger the room and the narrower its width, the larger its Ideal Window Area.

(5) The larger the room, the lower the energy consumption per unit of floor area.

(6) Rooms with a narrower width have lower energy consumptions due to the lower solar heat gains or losses through windows. This shows that rooms whose width is greater than its depth, as recommended in daylight guides, may experience higher daylight levels, but may not have the lowest energy consumption.

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